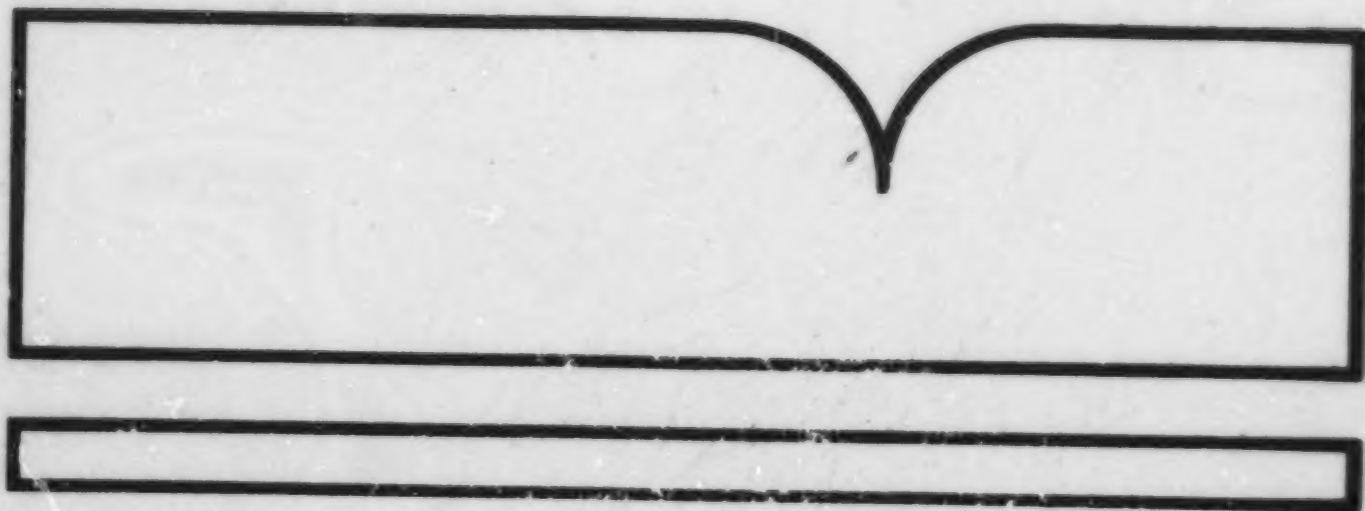


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TURBULENCE PARAMETERS IMPACTING DISPERSION IN AN
URBAN CONVECTIVE BOUNDARY LAYER

by

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16. ABSTRACT Turbulence measurements of the three dimensional wind components were collected by an instrumented research aircraft on 7 days in August 1976. These aircraft flights were conducted as part of the Regional Air Pollution Study (RAPS) urban boundary layer field program in St. Louis, Missouri. The focus of this research was to determine the magnitude and variation of characteristics of vertical velocity fluctuations in the afternoon convective boundary layer from data obtained at 150 m above ground. The vertical velocity time series for 22.5 km length segments were evaluated to obtain quantitative information on upward and downward turbulent motions in the urban convective boundary layer. Results of analysis revealed that vertical velocity distributions for both urban and nonurban segments displayed positive skewness and negative mode. Statistical results showed that the means and standard deviations of the upward and downward vertical velocities were 20% greater for the urban segments. The fractional amount of time spent in upward motions was consistently less than in downward motions. In addition, the results of comparisons of the size of the largest updraft, convective boundary layer height, and the vertical velocity spectral peak wavelength are presented.		
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TURBULENCE PARAMETERS IMPACTING DISPERSION
IN AN URBAN CONVECTIVE BOUNDARY LAYER

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1. INTRODUCTION

Vertical dispersion of pollutants emitted into the convective boundary layer (CBL) is highly dependent on the magnitude and structure of turbulence. Observations of vertical motions in the CBL show both well-defined updrafts (i.e. thermals) originating in the surface layer and extending through a substantial part of the CBL, and downdrafts containing air entrained into the CBL from aloft. These turbulent eddies play an important role in transporting and mixing pollutants vertically in the CBL. Considerable advances in understanding pollutant dispersion has been provided by results of convection tank experiments of Deardorff and Willis (e.g. Willis and Deardorff, 1983) and from recent numerical model simulation results (e.g. Misra, 1982; Weil, 1983). However, experimental observations are necessary to provide information for model parameterizations of turbulence and for model verification. Examinations of the detailed structure of convective eddies over land have been performed by Manton (1977) and Coulman (1978) while Lenschow and Stephens (1980) and Greenhut and Khalsa (1982) studied thermals in the marine boundary layer.

This paper presents the results of various analyses of turbulence measurements of the vertical velocity component obtained above the variable land use and roughness features of a large urban area. The data were

* On assignment from the National Oceanic and Atmospheric Administration,
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collected by an instrumented aircraft in the lower part of the CBL in the St. Louis, Missouri metropolitan area during the Regional Air Pollution Study (RAPS). Emphasis in this analysis was given to data obtained over the center part of the city and a comparison is made with the results from selected nonurban locations above agricultural land. Analyses of the detailed spatial variation of turbulence parameters and fluxes are documented in Ching et al. (1984), while Hildebrand and Ackerman (1984) present vertical profiles of turbulence variables and turbulent energy terms for St. Louis. Quantitative results on size and number of updrafts and downdrafts are presented. In addition, comparative results for different length scales, which include the depth of the CBL (Z_i), the wavelength (λ_w) at the peak in the vertical velocity spectrum, and the width of the largest updraft, are discussed.

2. EXPERIMENTAL DESIGN AND MEASUREMENTS

The data presented in this study were collected by the NCAR (National Center for Atmospheric Research) Queen Air N304D research aircraft. It was equipped with an inertial navigation system, a gust probe system mounted to a boom located in front of the aircraft, and an on-board computer for digital recording and for real-time display of measurements. Fast-response sensors were capable of providing rapid fluctuation measurements of the three dimensional wind components, temperature, and moisture. Raw measurements were sampled at a rate of 16 s^{-1} . After data processing and averaging, the turbulence data were reduced to 8 s^{-1} . More details about the instrumentation and data acquisition system in this aircraft were discussed by Lenschow et al. (1978).

St. Louis is typical of other large urban areas as it is composed of a variety of land uses and exhibits a unique land use distribution pattern which is described and shown in Auer (1978). The flight pattern performed during the field experiments, superimposed on a land use map slightly modified from that in Auer, is displayed in Figure 1. Flight paths were performed over various land uses in the metropolitan area. An additional flight path, not shown in Figure 1, was situated along a

southeast to northwest line traversing the city. Each horizontal run was approximately 70 km long at a nominal flight altitude of 150 m above ground, which corresponded to a normalized height from 0.10 to 0.20 Z_i . Several flights were conducted on selected fair weather days to determine both the temporal and spatial variations of turbulence.

3. DATA ANALYSIS METHODS AND RESULTS

The vertical velocity data analyzed in this study were taken from flight runs conducted during the convective period between 1100 and 1530 CDT on August 8-11 and 18-19, 1976. Each run was partitioned into five minute segments which corresponded to a length of about 22 km with a three minute overlap between adjacent segments. The midpoint of each segment is depicted by a circle on the flight runs in Figure 1. The focus of the statistical results is for the urban segments which are denoted by the filled circles. The mean vertical velocity was removed from the time series series of each segment. Representative vertical velocity (w') time series for the urban and nonurban segments are shown in Figure 2. Numerous updrafts and downdrafts are apparent in both time series, however, the vertical motions appear to be more vigorous in the urban area. Vertical velocity distributions were determined from the time series at 0.1 m s^{-1} intervals. The average results derived from urban and nonurban segments are displayed in Figure 3. Both distributions exhibit positive skewness and each has a negative mode. These results are in agreement with those from other experimental measurements in the CBL over land (Caughey et al., 1983). The nonurban distribution shows about a 20% greater frequency of small vertical velocities. A crossover appears at 1 m/s on both sides of the distributions. Larger positive and negative w' have slightly greater probability densities (P) in the urban segments. Thus, stronger vertical motions were found more frequently over the urban area.

Table 1. Results of Turbulent Vertical Velocities

Segment		σ_w	S	K	Z/Z_1	N
URBAN	X	1.10	0.49	-0.16	0.15	33
	SD	0.15	0.11	0.31		
NONURBAN	X	0.92	0.50	0.20	0.15	33
	SD	0.14	0.20	0.43		
ALL	X	0.98	0.49	-0.05	0.15	188
	SD	0.17	0.16	0.38		

X = mean, SD = standard deviation about the mean,
N = number of segments

Statistical results of w' for the urban, nonurban, and "all" segments are given in Table 1. The notable difference in these statistics among the segments is in the mean value of the vertical velocity standard deviation (σ_w), which is 20% larger for the urban than nonurban segments. The positive values for the coefficient of skewness (S) indicate that the w' distributions exhibit distinctive longer tails. A positive S is typical of w' distributions during unstable conditions, as observed in Figure 3, and reveals the existence of strong convective updrafts. Even though S was the same for the different segments, the third moment (w'^3) was significantly larger for the urban segments. The results for kurtosis (K), the peakedness of a distribution relative to the normal distribution, reveal of mean value of near zero ($K=0$ for a normal distribution), however, there was variability as revealed by the relatively large SD's.

Table 2. Statistics for Positive and Negative Vertical Velocities

Location		F_-	F_+	w'_-	w'_+	σ_{w-}	σ_{w+}
URBAN	X	.55	.45	-.81	1.00	.96	1.25
	SD	.014	.014	.12	0.15	.13	0.18
NONURBAN	X	.55	.45	-.67	0.82	.81	1.03
	SD	.018	.018	.12	0.12	.15	0.15
ALL	X	.55	.45	-.72	0.88	.86	1.10
	SD	.16	.016	.14	0.16	.016	0.19

Separate statistics were determined for positive (w'_+) and negative (w'_-) vertical velocities. The results are given in Table 2. On average, the fractional (F) amount of time in upward motions is consistently less than F for downward motions, which implies that pollutants released into the CBL will experience downward motions a greater percentage of the time. The magnitude of w'_+ and w'_- , and the standard deviations of the upward (σ_{w+}) and downward (σ_{w-}) velocities are about 20% greater for the urban segments. The results for all segments were between the urban and nonurban values.

It is of interest to normalize these parameters by the local convective velocity scale $W^* = (g w' T'_0 Z_i / T_0)^{1/3}$. The value of W^* was computed for each segment. The surface heat flux ($w' T'_0$) was derived by extrapolation assuming a linear heat flux profile from the flight level to Z_i where a value of $-0.2 w' T'_0$ was assumed. Heat flux differed by a factor of two or more across the metropolitan area (Ching et al., 1984). Estimates for Z_i were derived from lidar aerosol backscatter profiles obtained continuously at an urban site. The results were: $w'_-/W^* = -0.50$, $w'_+/W^* = 0.60$, $\sigma_{w-}/W^* = 0.60$, and $\sigma_{w+}/W^* = 0.80$. These were valid for both urban and nonurban segments. The similarity between urban and nonurban results suggests that W^* is the appropriate scaling velocity even in an urban area. SD for each of these ratios was about 10% of the mean values.

Various ad hoc techniques have been employed to quantify the structure of thermal eddies (Lenschow and Stephens, 1980; Greenhut and Khalsa, 1982). These methods are criteria dependent, but permit a comparison between urban and nonurban measurements. Time series were evaluated with the method of conditional sampling by a procedure similar to that discussed by Greenhut and Khalsa (1982). Initially, the value of an indicator function (I) was set at +1 for positive and -1 for negative w' . Requirements were that a nonzero value of I remain the same sign for at least 0.5 s (i.e. about 35 m) and that within a section, w' exceed a threshold value of greater than σ_{w+} or σ_{w-} to denote an updraft or downdraft event, respectively. The indicator function time series was modified

based on the above criteria to delineate only updraft and downdraft sections, while the remainder was designated as "environment". Figure 2 shows examples of the resulting indicator function. The minimum time criterion was established to eliminate small events, and the threshold value corresponded to a threshold multiplier of 1 as in Greenhut and Khalsa. The size (width) of an event was determined by the product of the aircraft speed and the amount of time the indicator function was nonzero. Results from this conditional sampling method are presented in Table 3.

Table 3. Conditional Sampling Results

Location		d (m)	d_p (m)	n (Event/km)
URBAN	UP	368	1154	1.0
	DOWN	296	1145	1.3
NONURBAN	UP	324	905	1.1
	DOWN	264	947	1.4
ALL	UP	337	992	1.1
	DOWN	268	964	1.4

d = width of an event, d_p = width of the largest event, n = event density

These results reveal that the mean and extrema updrafts were larger for the urban segments. The number density of downdraft events exceeded that for updrafts in both urban and nonurban segments. Further, differences in n between urban and nonurban segments were small. The distribution of normalized event sizes (d/Z_i) was determined at 0.05 Z_i increments over 0.1 Z_i intervals. The distribution of d/Z_i for updrafts in the urban segment (Figure 4) is similar to that found by Greenhut and Khalsa. The highest frequency of updraft size was between 0.15 Z_i and 0.2 Z_i . Similar results were found for the nonurban segments, except there were fewer large updrafts.

Another parameter that describes the turbulent eddies is the vertical length scale, λ_w , defined as the peak of the vertical velocity spectrum. Spectra were obtained from a standard fast Fourier transform routine as discussed in Clarke et al. (1982). Comparisons were made between the width of the largest updraft (d_p), Z_i , and λ_w . The mean values of λ_w/Z_i were 1.54 ± 0.67 for the urban segments and a slightly smaller value for the nonurban locations of 1.36 ± 0.45 . The results of a linear regression for individual values of λ_w and Z_i revealed a correlation coefficient (R) of 0.53 for the urban segments, while an R of 0.36 was found between d_p for updrafts and λ_w . The mean value of d_p/Z_i at the urban sites was 1.04; however, an R of only 0.13 was obtained from a comparison of individual values of d_p and Z_i . Additional analysis is underway to determine factors which may be causing this large scatter, such as, variations in wind speed and differences between aircraft heading and wind direction.

4.0 SUMMARY AND CONCLUSIONS

Results of analyses of vertical velocity time series from aircraft measurements in the lower part of the CBL over St. Louis reveal that the w' distribution is positively skewed and has a negative mode in urban and nonurban locations. These results support the numerical model simulation results for w' distributions (Lamb, 1978). Statistical results revealed larger values for upward and downward w' over the urban area. Yet, the scaling of velocity moments by W^* appears valid in the urban area. Comparisons of various lengths scales reveals that the size of the largest eddies was the same as Z_i , but there was relatively large scatter when individual values were compared. The vertical velocity spectral peak wavelength was $1.5 Z_i$ for the urban segments, which is in agreement with experimental results in uniform remote terrain.

DISCLAIMER - This is an extended abstract of a presentation and does not necessarily reflect EPA policy.

REFERENCES

- Auer, A. H., 1978: Correlation of land use and cover with meteorological anomalies. J. Appl. Meteor., 17, 636-643.
- Caughey, S. J., M. Kitchen, and J. R. Leighton, 1983: Turbulence structure in convective boundary layers and implications for diffusion. Bound. Layer Meteor., 25, 345-352.
- Ching, J. K. S., J. M. Godowitch, J. F. Clarke, and A. H. Auer, 1984: Urban scale variations of turbulence parameters and fluxes. In preparation.
- Clarke, J. F., J. K. S. Ching, and J. M. Godowitch, 1982: An experimental study of turbulence in an urban environment. U. S. Environmental Protection Agency, Research Triangle Park, NC, Tech. Report, EPA 600/3-82-062.
- Coulman, C. E., 1978: Boundary-layer evolution and nocturnal inversion dispersal - Part II. Bound. Layer Meteor., 14, 493-513.
- Greenhut, G. K., and S. J. S. Khalsa, 1982: Updraft and downdraft events in the atmospheric boundary layer over the equatorial Pacific Ocean. J. Atm. Sci., 39, 1803-1818.
- Hildebrand, P. H., and B. Ackerman, 1984: Urban effects on the convective boundary layer. J. Atm. Sci., 41, 76-91.
- Lamb, R. G., 1978: A numerical simulation of dispersion from an elevated point source in the convective planetary boundary layer. Atm. Env., 12, 1297-1304.
- Lenschow, D. H., C. A. Cullian, R. B. Friesan, and E. N. Brown, 1978: The status of air motion measurements on NCAR aircraft. Fourth Symp. on Meteor. Obs. and Instrumentation. Preprints, Amer. Meteor. Soc., Boston, MA.
- Lenschow, D. H., and P. L. Stephens, 1980: The role of thermals in the convective boundary layer. Bound. Layer Meteor., 19, 509-532.
- Manton, M. J., 1977: On the structure of convection. Bound. Layer Meteor., 12, 491-503.
- Misra, P. K., 1982: Dispersion of non-bouyant particles inside a convective boundary layer. Atm. Env., 16, 239-243.
- Weil, J. C., 1983: Applications of advances in planetary boundary layer understanding to diffusion modeling. Sixth Symp. of Turb., Diff. and Air Poll. Preprints, Amer. Meteor. Soc., Boston, MA.
- Willis, G. E., and J. W. Deardorff, 1983: On plume rise within a convective boundary layer. Atm. Env., 17, 2435-2447.

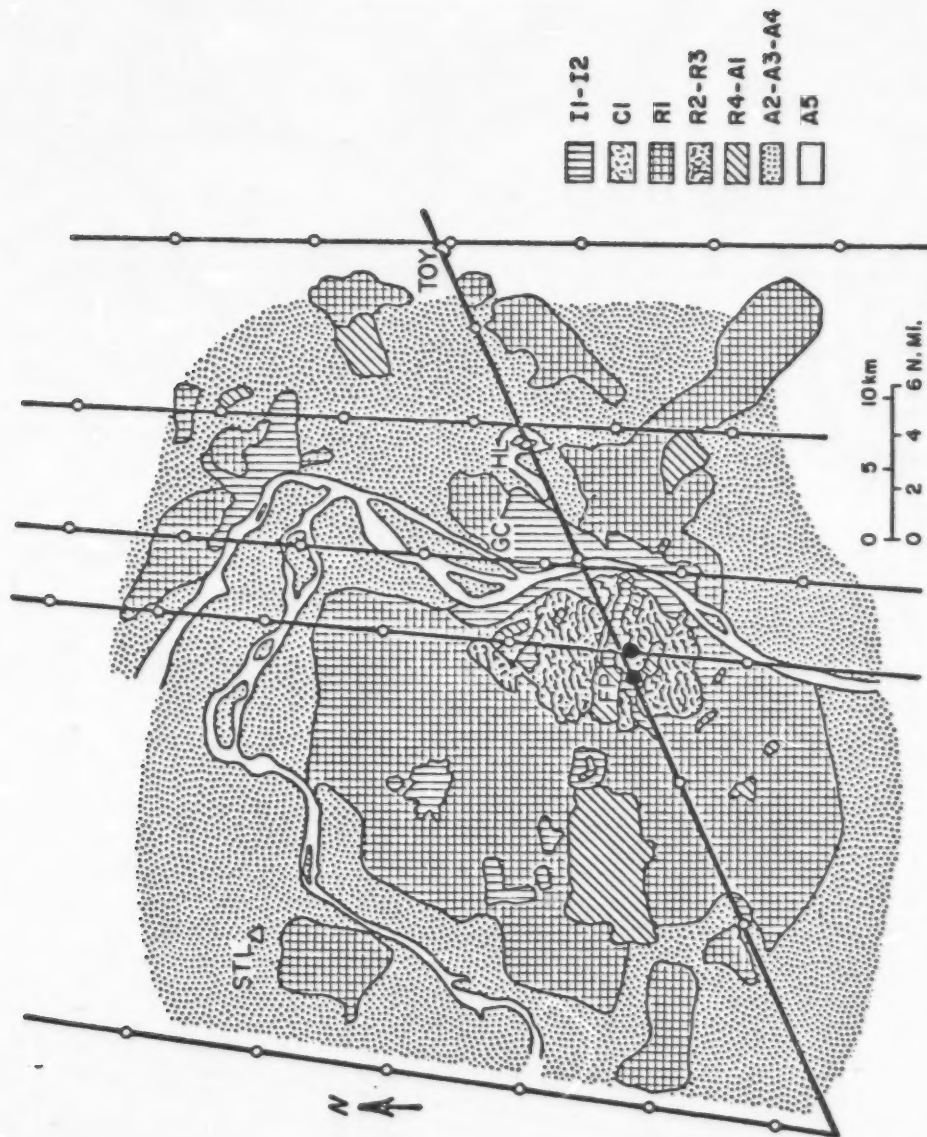


Figure 1. Aircraft flight pattern and land use map of the St. Louis, MO metropolitan area. Circles denote the midpoints of 22 km overlapping segments.

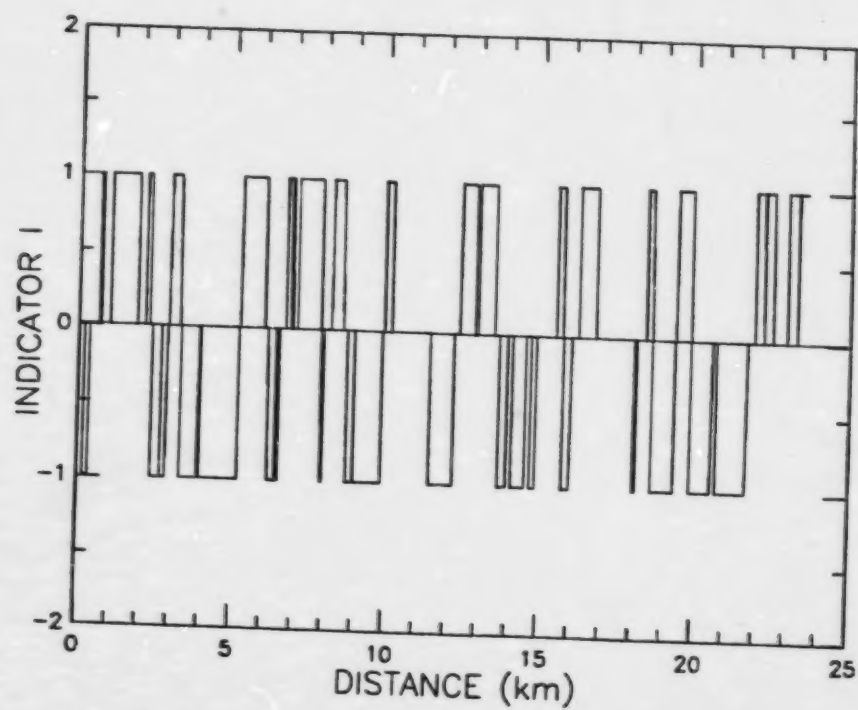
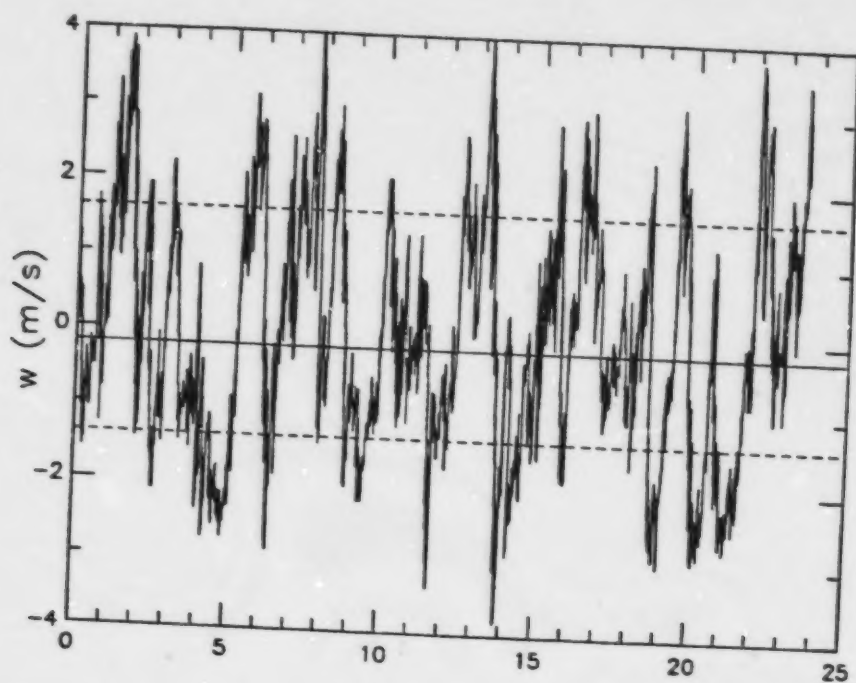


Figure 2a. Vertical velocity fluctuations for an urban segment.
The indicator function denotes updraft (+1) and
downdraft (-1) events.

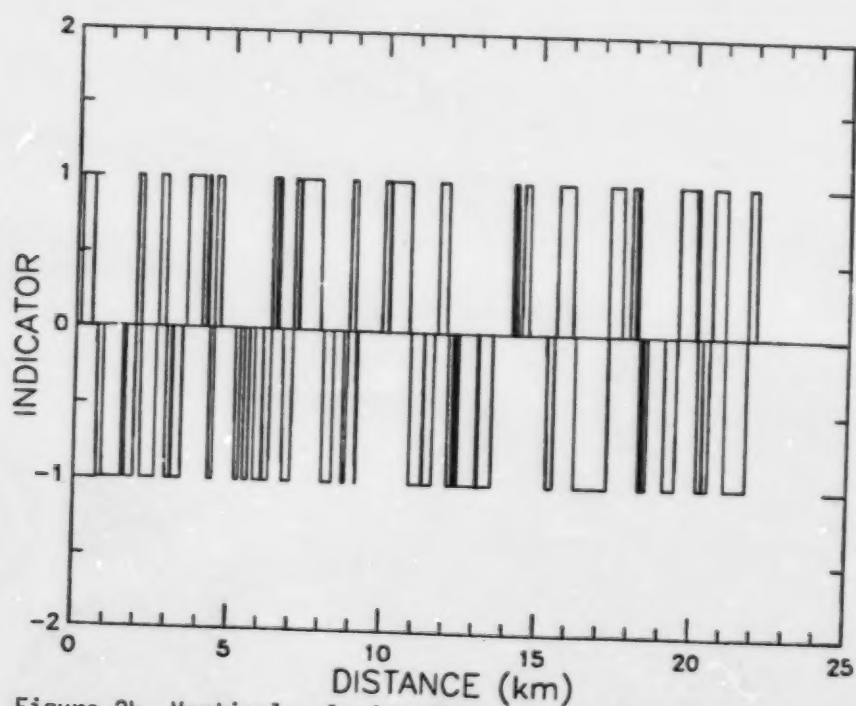
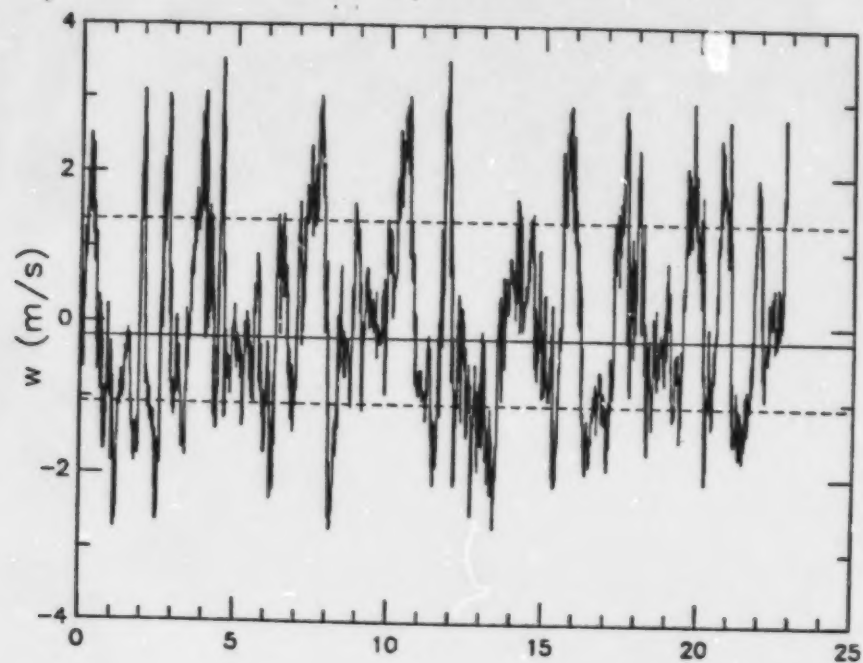


Figure 2b. Vertical velocity fluctuations for a nonurban segment. Solid line in the w' series represents the median w' . Dashed lines are the standard deviations for positive and negative w' .

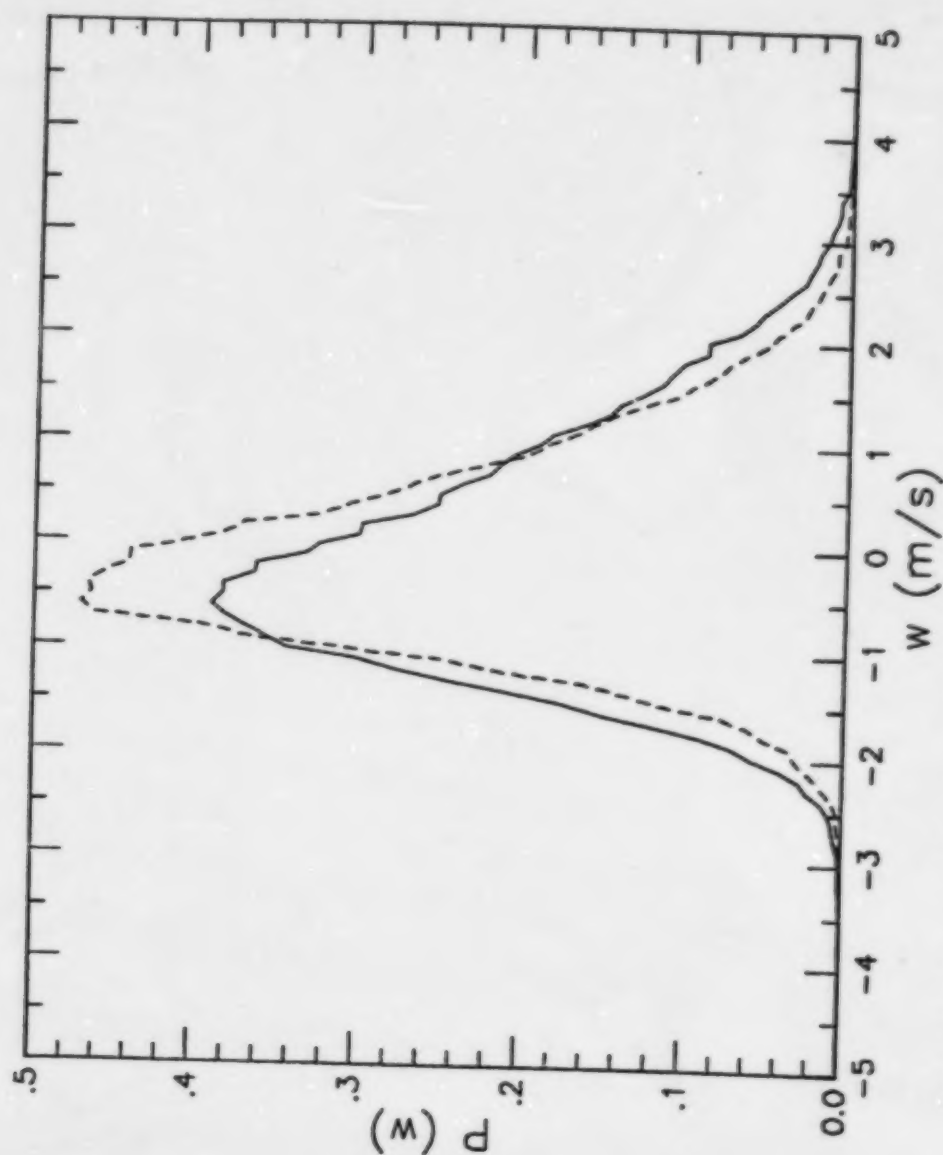


Figure 3. Probability density, $P(w)$, distribution of vertical velocity fluctuations for the urban (—) and nonurban (---) segments.

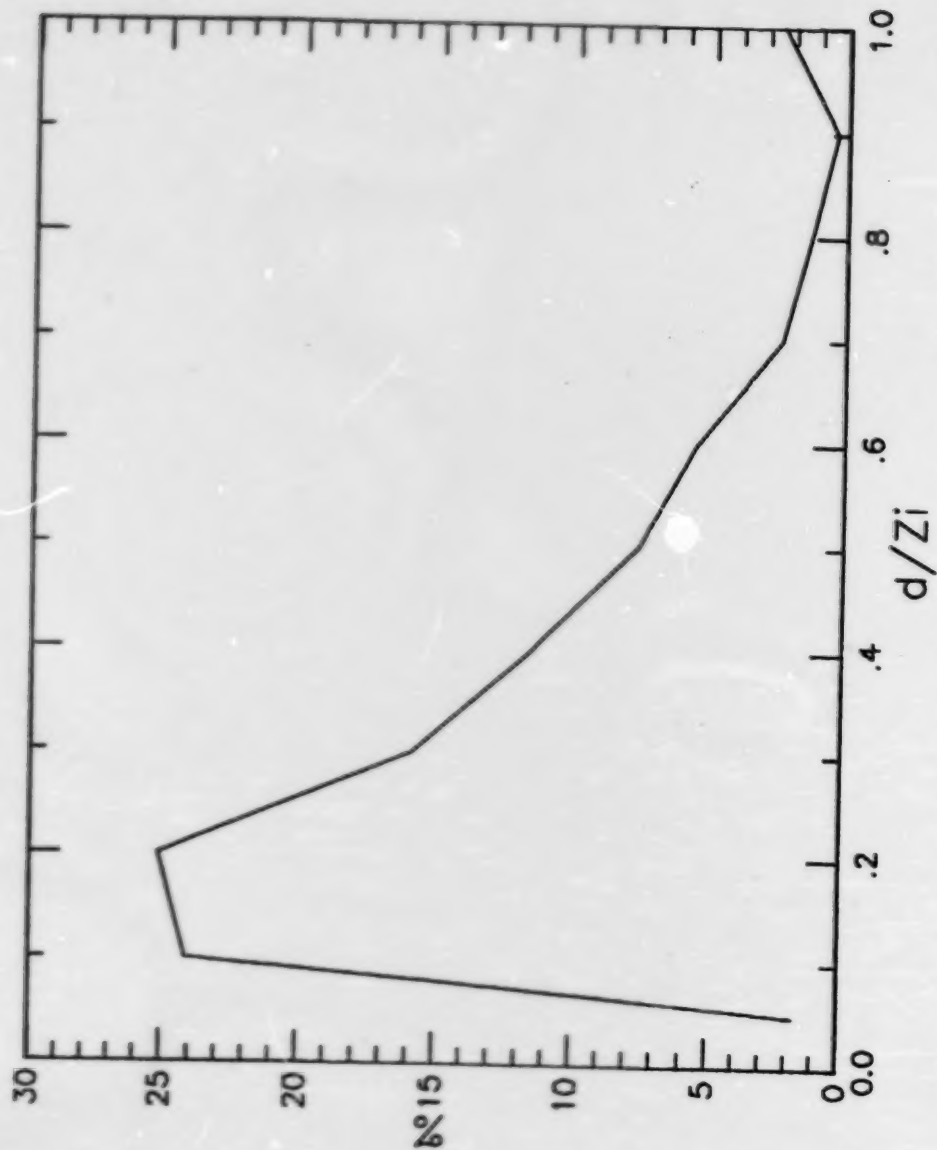


Figure 4. Distribution of normalized updraft size (d/Z_i) for the urban segments.